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Modulation Methods for Multi-Station Satellite Communication Systems

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For the first experiments on communication by satellite, wide-deviation FM has been used. This is partly because of the considerable experience with this type of operation on earthly microwave radio relay links, and also because conventional telephone channelling equipment uses FDM techniques. Future satellite communication systems will not necessarily use these techniques (although, because they would be simply an extension of conventional systems, there would be much advantage in doing so). This article analyses and compares three possible methods of modulation and hazards some opinions as to their relative merits and attractiveness.

1 INTRODUCTION

FUTURE WORKERS in the communication field will surely look back on the years 1962 and 1963 as two of the busiest in the history of long-distance radio communication, for during this period at least three active communication satellites are scheduled for launching and testing. These are Telstar, Relay and Syncom, the first two being of the medium altitude equatorial orbiting class and the latter being a 24-hour synchronous orbiting satellite.

At the time of writing, Telstar has been in orbit for about four months, during which time experimental transmissions of live television pictures and of multichannel telephony have been successfully achieved over trans-oceanic distances. World-wide participation is expected in the

Synchronous satellites offer formidable advantages, such as fewer satellites, much simpler tracking, regular scheduling and minimum interference with other services operating on a shared frequency basis. However, a fundamental characteristic of the 24-hour synchronous system is that a one-way trans-global delay of about 0.6 second must be tolerated — a delay which is large enough to render the circuit unsatisfactory to a percentage of speakers. Many long circuits, however, would be within the coverage of one satellite, when this delay would be halved (giving a two-way delay of 0.6 sec.). This is a figure which is probably acceptable to the majority of users provided that echoes are adequately suppressed.

The U.K. Post Office in their proposal made in May 1961 for a Commonwealth/Europe World-Wide Satellite Communication System¹ suggest the employment of active, station-keeping, attitude stabilized satellites in circular equatorial orbits at heights between about 5 000 and 10 000 n. miles. Representative examples of the 24-hour synchronous satellite system are seen in the American proposals made, for example, by the R.C.A., G.T.E and I.T.T.

2.1 AREA OF COVERAGE

The service area of a synchronous satellite is about 40% of the earth's surface, whereas the corresponding figure for a 6 000-mile altitude satellite is about 25%. The synchronous satellite must therefore cater for a correspondingly larger number of ground stations within its cover.

2.2 WORLD TELEPHONE DISTRIBUTION

Because of the unequal distribution of land masses and population over the world's surface, it is possible to choose a single synchronous satellite position which will cover countries in which over 90% of the world's telephones are located. Thus, considerably less than 10% of the channel capacity need be reserved for interconnection with an adjacent satellite repeater, as in general the longest calls are the least frequent. In comparison with this, the medium-altitude satellite system will require interconnection with the next, and the next but one, satellite repeater (i.e. three streams of trunk traffic will be carried by each satellite). These three streams, however, are not each of equal volume so that the neces-

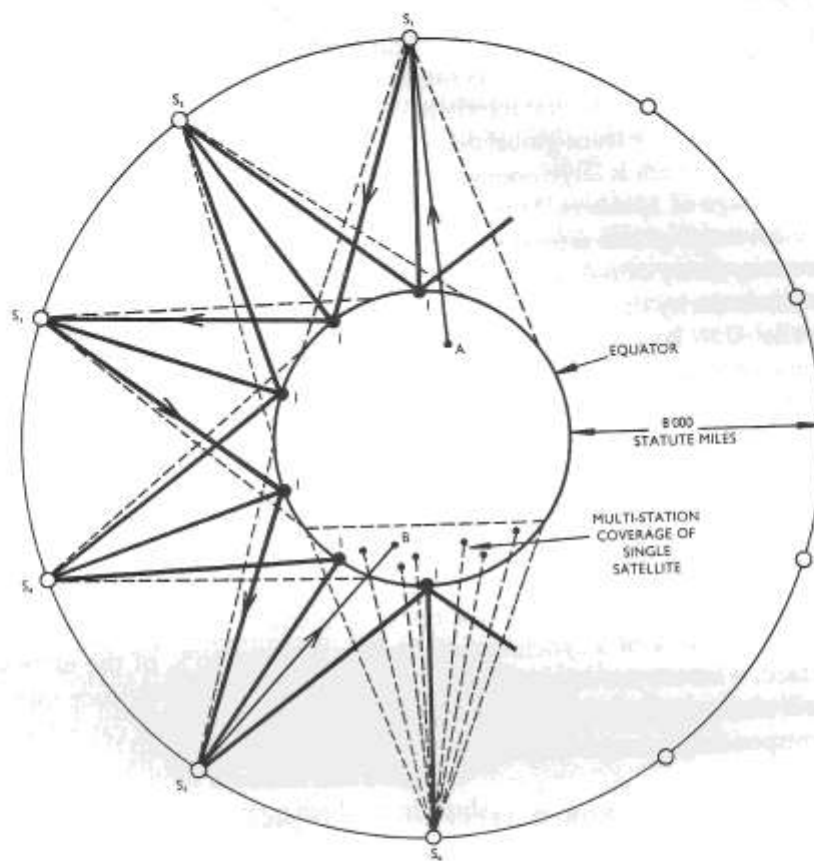


Fig. 1. Trunk route diagram for global medium-altitude satellite telecommunications system.

S_1, S_2 , etc. = Station keeping satellites in circular equatorial orbits
 I = Interconnection centres, located near the Equator

Possible trunk routing is shown by heavy lines. The most direct path between A and B , on opposite side of the globe, traverses 3 repeaters as shown by arrows. Long distance trunk traffic might utilize about 20% of the total capacity of each satellite

sary reservation for trunk working per medium-altitude satellite would perhaps be twice the percentage figure for the case of a synchronous satellite. Figs. 1 and 2 illustrate this point.

2.3 WORLD TELEPHONE TRAFFIC PATTERN

In any world-wide communication system there is a tendency for the heaviest traffic to move westward with the sun. This effect is present in a medium-altitude satellite system as well as in a synchronous system, although the consequences are different. In the former case there will be a fluctuation of total traffic demand to a particular satellite from hour to hour, according to both its relative position to ground communication

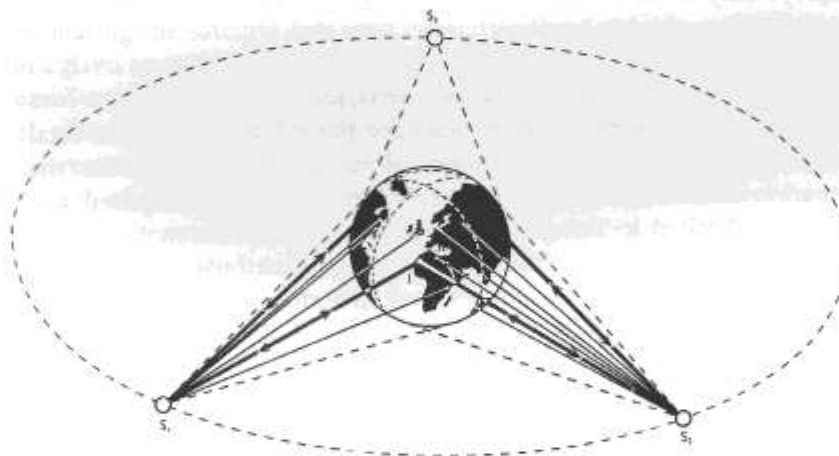


Fig. 2. Trunk routing diagram for global synchronous satellite telecommunications system.

S_1 , S_2 and $S_3 = 3$ satellites in 24-hour equatorial orbits
Only 3 interconnection centres are required suitably
located near the Equator

Possible trunk routing is shown by heavy lines. Only one interconnection centre is required for any circuit. Long distance trunk traffic might utilize about 10% of satellite capacity

centres and also to the relative position of the sun at the time. In contrast to this, the synchronous satellite covers the same communication centres all the time. Owing to its large coverage, there is a tendency for the total capacity requirement to stay constant, with the sun's relative movement, but there will be a traffic movement westward within the coverage area. Ideally, the assignment of the total channel capacity of a synchronous satellite between the different centres within its coverage must be flexible if the satellite is to be kept fully loaded. If this principle of optimum assignment is realized, the system will more efficiently use the total channel capacity of all its satellites than could the medium-altitude scheme. This is only another way of saying that a system employing 12-16 satellites to serve all the ground stations must be more wasteful of channel capacity than is characteristic of a synchronous system which employs only three satellites, each of roughly double the capacity of a single medium-altitude satellite.

2.4 OTHER FACTORS

These three considerations affect plans for the sub-division of the total baseband allocation, and the choice of modulation system, for the ground-to-satellite transmissions. A truly flexible system is required, and this is not limited to being a requirement of the synchronous system only, for in the course of an orbit a medium-altitude satellite will experience even more rapid changes, both in numbers of ground stations engaged and in the number of channels associated with these stations.

Reasonably efficient use of the system capacity requires that blocks of as few as 12 telephone channels may be allocated to, or removed from, any ground station assignment at any time.

Other effects associated with the choice of orbit are :

- (a) Reduced Doppler shift (near zero) in the synchronous system.
- (b) Increased path attenuation in the case of the synchronous satellite requires ground station and satellite powers of about +3 dB with reference to those of an equal-capacity medium-altitude satellite system to give equal performance. The great power of the ground station transmitters will increase the possibility of interference from synchronous satellite ground stations into other systems, in

comparison with that existing in the medium-altitude case, and may encourage the use of modulation methods which give least interference per unit bandwidth (e.g. wideband modulation techniques which result in energy spreading).

Since the required channel capacity per satellite in the synchronous system is usually greater than that required in a medium-altitude system, the satellite transmitter power must be further increased by perhaps 3 dB to give an equivalent channel performance. (In the FM-with-feedback case, this power increase may be avoided at the expense of widening the occupied RF bandwidth by a factor of approximately $\sqrt{2}$ times the fractional increase in the number of channels required.)

3 MULTIPLE ACCESS METHODS

In sharing the satellite baseband capacity between the ground stations in a given area, time division methods are theoretically possible. Schemes based on this principle would be so cumbersome in practice (on account of either satellite movement, or of different absolute time delays between a given stationary satellite and individual ground stations) that the use of frequency division to separate the emissions of the various ground stations is vastly to be preferred. In considering FDM schemes, the single sideband technique seems to offer the simplest and most flexible arrangement. It is the most economical of all possible modulation systems in the use of radio frequency spectrum.

Automatic transmitted power level and frequency correction of each ground transmitter may be applied by means of a control link from the satellite. This will correct for distance variation and for average Doppler shift, although the Doppler contraction or stretching of the baseband associated with each ground station emission will still be apparent at the output of the satellite receiver. The need for Doppler shift correction of the ground transmitter will, of course, be removed if less efficient use is made of the RF spectrum by (a) placing sufficiently large guardbands between the frequency bands allocated to each station, and (b) using a system of modulation in which either a carrier or reference carrier is transmitted.

If one disregards the technical problems and possible equipment complications associated with the generation of SSB multichannel FDM telephony signals in the microwave bands at the ground transmitting sites, there is no doubt that SSB transmission from ground to satellite offers the most flexible solution to the multiple access problem. The technical problems, however, are formidable and at present weigh heavily against the choice of SSB. The achievement of sufficient amplitude linearity, and the provision of continuous Doppler correction for each channel, are particularly difficult to solve.

4 POWER AND BANDWIDTH REQUIREMENTS FOR SATELLITE LINKS

4.1 SATELLITE-TO-GROUND PATH

Since it is more difficult to achieve a given signal-to-thermal noise ratio on the satellite-to-ground path than on the upward transmission path, due to increased receiver noise and limited satellite transmitter power (at present within the range 1–10 W), the former path has been given prominence in calculations of power and bandwidth requirements for different modulation systems.

In a former article³ the required signal-to-thermal noise ratio for the satellite-to-ground path was assumed to be 50 dB unweighted in a 4 kc/s band. Noise contribution due to thermal noise in the other path and to intermodulation noise in both paths could reduce this figure to 47.7 dB unweighted in a 4 kc/s band. This corresponds to a total unweighted noise power of 7 500 pW in a 3.1 kc/s telephone channel, which is the maximum radio equipment noise allowance recommended by the C.C.I.R. over a 2 500 km reference circuit. A 1 200-channel system was considered, requiring a base-bandwidth of about 5 Mc/s.

A ground receiving system equivalent noise temperature of 40°K was assumed, corresponding to an input noise level of -136 dBW in a 50 Mc/s RF bandwidth.

Considering the satellite-to-ground transmission, the bandwidths and minimum required transmitter powers at orbital heights of 6 000 miles and 22 300 miles are given in Sections 1(a), 1(b) and 1(c) of Table I, for

Table 1
POWER AND BANDWIDTH REQUIREMENTS FOR TRUNK AND MULTI-STATION WORKING

Direction and Mode of Transmission	Modulation System	RF Bandwidth (Mc/s)	Minimum Transmitter Power for Orbital Height of: 6 000 miles 22 300 miles
1 SATELLITE-TO-GROUND Thermal noise -60 dBmO unweighted in each channel Trunk or Multi-Station Working Up to 1 200 telephone channels	(a) Wideband FM with feedback (b) PCM carried by bi-polar VSB (c) SSB	50 50 5	3 W 4 W 1.5 W 2.5 W 10 W mean 20 W mean
2 GROUND-TO-SATELLITE Thermal noise -60 dBmO unweighted in each channel 2.1 Trunk Working Transmission of 1 200 channels between ground stations 2.2 Multi-Station Working	(a) Wideband FM with feedback (b) PCM carried by bi-polar VSB (c) SSB (a) Wideband FM with feedback (b) PCM carried by bi-polar VSB (c) SSB	50 50 5 5 Mc/s channels (excluding guard bands) 5 Mc/s channels (excluding guard bands) 0.5 Mc/s channels	1.5 kW 3 kW 1 kW 2 kW 8 kW mean 16 kW mean 200 W 400 W 100 W 200 W 1.1 kW mean 2.2 kW mean

* These powers may be decreased by 9 dB if pulse regeneration is employed in the satellite

three systems of modulation. Absolute power levels are about 4 dB lower than those given in Reference 2, resulting from a corresponding increase in assumed total aerial gain, this increase being justified by recent improvements in the design of large aperture tracking aerials and in attitude stabilization techniques for satellites.

The transmitter power requirement figures shown apply for any frequency within the 1–10 Gc/s 'window' in the atmosphere, since constant beamwidth satellite aerials and constant aperture ground aerials are assumed. Typical frequencies are 6 000 Mc/s and 4 000 Mc/s for the upward and downward paths respectively. Atmospheric attenuation has been assumed to be insignificant at these frequencies for ground aerial elevations above about 5°. Experience with Telstar has already shown that this assumption is conservative.

The power and bandwidth figures for the satellite-to-ground path, given in Sections 1(a), 1(b) and 1(c) of Table I, apply equally to two ground stations loaded with 1 200 channels or to the multi-station case, since the same method of transmission from the satellite is used in both.

An examination of the required transmitter powers for the downward path given in Table I shows that, under the conditions assumed in the calculation, the relative minimum power levels for SSB, wideband FM and PCM are 0 dB, -7 dB and -9 dB respectively. The SSB level given is the mean power exceeded for 1% of the time; the peak envelope power will be about 7 dB above this level.

Bandwidths occupied are 5 Mc/s for SSB and 50 Mc/s for FM and PCM. The 50 Mc/s PCM bandwidth assumes vestigial sideband transmission of the spectrum resulting from bi-polar modulation of an RF carrier, with 10% bandwidth allowance for the vestigial edge. It assumes that the signal components occupying a bandwidth of $1/1.3t$ where t is the time occupied by one code element.

4.2 GROUND-TO-SATELLITE PATH

It is now of interest to examine the receiver input level requirements for the ground-to-satellite path for both 2-station (trunk) and multi-station uses.

An equivalent noise temperature for the satellite aerial and receiver

of about $3\,000^\circ\text{K}$ is assumed. Lower temperatures than 300°K are not practicable in a satellite-borne receiving system which has its aerial looking towards the earth. A satellite receiver with either a microwave mixer or a travelling wave tube first stage might be expected to have a receiver noise temperature, T_n , of about nine times this minimum (i.e. $2\,700^\circ\text{K}$, corresponding to a receiver noise figure of about 10 dB) when the receiving system equivalent noise temperature will be $300 + T_n = 3\,000^\circ\text{K}$. The use of a low noise parametric amplifier first stage in the receiver would reduce this to an equivalent noise of about 400°K , but since sufficient power is available from the ground transmitters to operate at a receiver noise temperature of $3\,000^\circ\text{K}$, the additional complication and the possible unreliability of present equipment associated with these amplifiers is not favoured.

The thermal noise level at the satellite receiver input operating at $3\,000^\circ\text{K}$ will then be $10 \log \frac{3\,000}{40} = 19$ dB higher than that appropriate to a ground receiving system at 40°K .

This has been taken into account in the figures shown in Section 2 of Table I. In addition, the thermal noise allowance at the output of each 4 kc/s channel on the ground-to-satellite path has been reduced to -60 dBmO (i.e. 10 dB reduction in absolute noise power, in comparison with that specified for the satellite-to-ground path) as the latter transmission is more difficult.

* In the case of FM, SSB and PCM without code regeneration in the satellite, the total difference in input level between ground and satellite receivers is $19 + 10 = 29$ dB. PCM with regeneration, however, shows an advantage here in that the required increase is only $19 + 1 = 20$ dB since, at the signal levels considered, a 1 dB increase in carrier-to-noise level with this modulation system will result in a 10 dB increase in S/N ratio at the channel outputs after decoding. The powers given under 2.1(b) and 2.2(b) of Table I assume that no code regeneration occurs in the satellite equipment, and these powers may therefore be reduced by 9 dB if regeneration is in fact employed.

It is worth noting that if the satellite power could be increased by about 3 dB then the ground station power may be reduced by 7 dB

relative to the levels shown in Table I. This applies to all three systems of modulation and is a consequence of a different distribution of relative noise contributions from each path.

The above discussion applies equally to trunk and multi-station operation. However, for the multi-station case, the required ground-station transmitter power and the occupied bandwidth are both reduced. Section 2.2 of Table I assumes 10 ground stations, each loaded with 120 channels, as the alternative to the trunk system case. Taking the SSB case as the basis of comparison, the required ground-station transmitter power and the bandwidth occupied for the alternative modulation systems are shown in Table II.

Table II
COMPARISON BETWEEN ALTERNATIVE
MODULATIONS—MULTI-STATION CASE

Modulation System	Relative Power (dB)	10 log (Relative Bandwidth)
SSB	0	0
FM	-7.5	+10
PCM	-10.5	+10

In reducing the number of channels by a factor of 10, the SSB and FM power requirements have reduced by -8.5 dB (the difference between the 1200-channel loading factor and that appropriate to 120 channels). In the PCM case the power requirement is exactly proportional to the bandwidth, which in turn is proportional to the number of telephone channels. Thus, reducing the number of channels by a factor of 10 reduces the required power by 10 dB. PCM has gained, on reducing the number of channels, in comparison with the other two systems. In all three systems the change in bandwidth has been proportional to the change in the number of channels.

An important point to consider in connection with multi-station working is the amount of separation necessary between channels occupied by different ground stations which simultaneously engage a single

satellite, in order to allow proper reception in the presence of out-of-band emissions, frequency drifts and Doppler shifts.

The sidebands associated with FM and PCM emissions reduce gradually at the edges of the nominal occupied bandwidth, and means will be required to limit this out-of-band radiation to avoid unduly wide guardbands. In both cases the phase/frequency characteristics of the transmission network must be highly linear. Doppler shift at the satellite receiver may amount to a maximum of about ± 30 kc/s, and this may either be allowed for in the guardbands provided, or correction could be made before transmission. Continuous correction would, of course, be necessary and could be predetermined (from a knowledge of the satellite orbit) or automatic (by means of a satellite-to-ground pilot link).

In the case of FM and PCM it seems preferable to employ slightly wider guardbands and so avoid the complication of frequency control.

The SSB case is different, in that the radiated bandwidth is precise. No unwanted distortion of the multichannel signal occurs after transmission through filters with sharp cut-off characteristics. Thus, individual channels, or groups of channels emanating from any ground station may be stacked closely in the frequency spectrum, without having to provide large guardbands. Again, these guardbands may either be made large enough to accommodate equipment drift and Doppler shift (when pilot carriers will be necessary) or Doppler correction must be applied at the transmitter, as described above. The fact that SSB occupies only 1/10 of the bandwidth necessary for the accommodation of the wideband FM and PCM emissions will, of course, make it easier to provide suitable guardbands in the SSB case.

The relative bandwidth occupancy of the three systems is illustrated in Fig. 3, which shows a type of channelling arrangement which would be suitable for trunk and multi-station working.

4.3 LINEARITY REQUIREMENTS

An acceptable figure for total permissible intermodulation power into any one channel at the output of the system is about -54 dBmO unweighted. This could be divided into an allowance of -57 dBmO for each path,

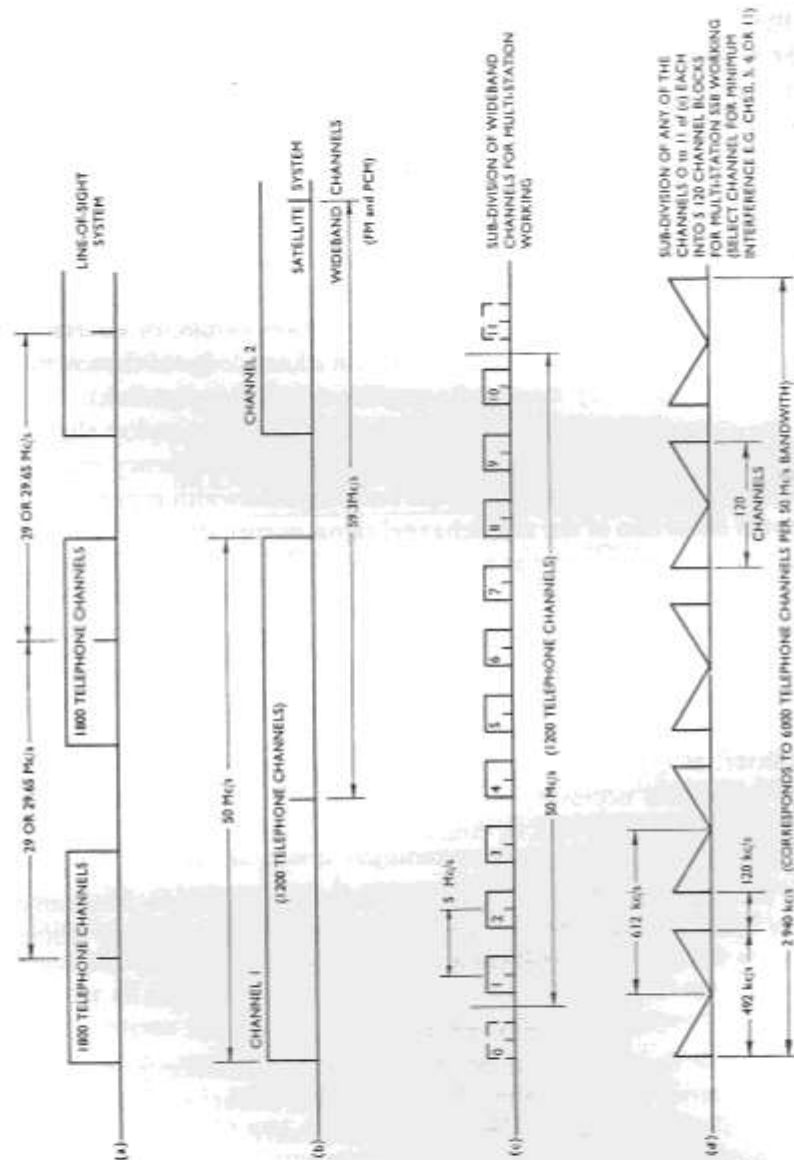


Fig 5. Example of channeling arrangement for trunk and multi-station working

In the case of SSB modulation it will be necessary to maintain the system amplitude linearity at this figure. All the equipment is involved in this requirement (i.e. ground transmitter, both the modulator and RF circuits, and satellite repeater (including demodulation circuits if these are provided)). If SSB is employed for downward transmission also, then the satellite modulator and RF amplifier, in addition to the ground receiver circuits, must be linear.

Phase linearity is not important for multi-channel telephony, but assumes moderate significance for television relay work.

The above considerations apply to both trunk and multi-station working.

The achievement of the required linearity in a FM system will require a system phase linearity corresponding to a group delay variation not exceeding a few millimicroseconds. The amplitude linearity requirement is absent in the RF and IF path but the frequency response must be good throughout, to avoid sideband distortion. The phase linearity requirement applies to the whole of the system. In addition, whenever modulation or demodulation occurs, there will be need for a high order of linearity of the modulator and demodulator characteristics.

In the case of ground-to-satellite multi-station working, great difficulty arises in passing more than one multichannel FM spectrum through a common transmission path (e.g. through a common IF or RF amplifier in the satellite repeater). In this instance, not only is a high degree of phase linearity essential, but at the same time amplitude distortion must not be excessive. Experiments in connection with two-way speech transmission through a common repeater carried by the Telstar satellite have already furnished some practical figures relating to intermodulation between at least two FM transmissions carried simultaneously by common repeater equipment on the satellite. The effect of loading a common repeater with 10 such emissions can probably be estimated from the results of these experiments.

In PCM systems linearity is unimportant and this applies to all parts of the system, including modulator and demodulator stages. If the method of carrying the code waveform via a radio frequency channel is to generate RF pulses (bi-polar or otherwise) corresponding to the code

1's and 0's and to transmit the double side-band information, then phase linearity of a high order is not necessary. VSB transmission of the RF spectrum however will require a certain degree of phase linearity (dependent upon the amount of overshoot tolerable), maintained over the frequency band in the region of the vestigial cut-off. In general, this requirement is not so severe as in the FM case, and may typically amount to the need to hold the phase error to less than about 5° over the RF bandwidth.

Intermodulation between PCM telephone channels sharing a common carrier on a time division basis (e.g. 120-channel transmission from one of the ground stations) will result from pulse distortions which cause energy transfer between one pulse interval and another. Usually this inter-element interference will take place between digits adjacent in time sequence, but multipath transmission with time delays of greater than about $1/3 \mu\text{S}$ could cause interference with pulses further removed. The latter condition is not expected to apply over a satellite path, but the need to minimize adjacent inter-element cross-talk will still arise. This effect is dependent upon the bandwidth shaping and phase linearity characteristics of the transmission circuits between encoder and decoder. Experiments show that pulse intermodulation is insignificant in a system employing bandwidths of about $1/1.3t$, when proper attention is paid to phase linearity.

Quantizing noise is characteristic only of PCM, and will appear at the system output, even in a circuit in which coding errors are absent.

Errors in output due to the inability of the system to resolve amplitude to better than one quantizing step cause a form of noise, the audible effect of which is different from thermal noise, since it is more spiky in nature. The magnitude of this noise may be reduced to any required degree by providing a sufficient number of steps. A code which uses 7 binary digits to convey the amplitude of each sample will cater for 128 steps. In order to take care of the large variation in level encountered in normal telephone circuits (of the order of 40 dB), pre-coder amplitude compression is necessary with expansion after decoding. Alternatively (or additionally) the steps may be staggered in amplitude, the smaller steps corresponding to the lower amplitudes.

By the use of such methods it is found that a 7-digit binary code will reduce quantizing noise to a barely noticeable level. Measured on a power meter, the noise level is certainly below the C.C.I.T.T noise allowance when a 7-digit system is properly set up, but its acceptance by users must await the results of adequate subjective tests. Additionally, the level of harmonic generation after compression, encoding, decoding and expanding should also be the subject of further measurement.

The pulse code waveform may be regenerated at any point in the system, and non-linear phase effects which might cause pulse distortion are therefore not cumulative over several paths. This applies also to noise of all kinds which may be removed by pulse regeneration. If either of these causes of error are large enough (so that in fact code errors do occur) then of course these errors will be transmitted to the decoder at the end of the system.

An important point to note in connection with pulse code systems is that a comparatively large amount of intermodulation may be tolerated between two code trains, which after modulation on to separate carriers are passed through a common transmission channel. Intermodulation of about -20dB relative to the amplitude of one of the carriers will not cause significant errors in the correct recognition of other pulse trains and therefore will not appear as cross-talk when decoded. For similar reasons, the use of quadrature carriers modulated by separate code trains, each carrying half the total information, is feasible. Double side-band transmission would be necessary, and the bandwidth occupancy for a given channel capacity would be about equal to that characteristic of VSB transmission.

In respect of its characteristic tolerance of high intermodulation levels, the pulse code system is more suited to ground-to-satellite multi-station use than are either of the other two systems of modulation.

5 EQUIPMENT CONSIDERATIONS

5.1 GROUND EQUIPMENT

5.1.1 FM Systems

Points of difference between line-of-sight link equipment and satellite ground station equipment using FM are listed on the following page.

Satellite ground equipment employs:

- (a) Large tracking aerials;
- (b) A low noise maser pre-amplifier;
- (c) Wide deviation (about ± 20 Mc/s peak compared with about ± 4 Mc/s peak for line-of-sight links) and a correspondingly wide RF channel (e.g. 50 Mc/s);
- (d) 'Frequency Following' or feedback from the discriminator output to control the frequency of the local oscillator;
- (e) Transmitter power outputs in the microwave region in the power range 1–10 kW;
- (f) Special baseband equipment with group demodulators, frequency-corrected for Doppler differences over the baseband.

With the exception of the low noise wideband maser, which is a new device fortunately available at a time when it is practically essential to the working of the system, the other components and techniques listed above are extensions to known techniques.

The use of wide deviation implies improvements to such components as modulators, phase-linear wideband amplifiers, and wideband radio frequency components having low VSWR.

Frequency-following techniques have been known for some years, but the requirement to provide a loop feedback of about 20 dB over the 5 Mc/s bandwidth employed in trunk working sets a difficult stability problem. For 120-channel multi-station working, this amount of feedback has already been achieved over the necessary 500 kc/s baseband.

The attainment, at a frequency of about 6 000 Mc/s, of 20–30 dB more transmitter power than is required for line-of-sight links is a development and manufacturing problem.

Baseband Doppler correction is a novel requirement but presents no new problems in the field of electronic servo systems.

5.1.2 PCM System

In the case of PCM the ground equipment presents no great difficulty.

For trunk working the requirement is to provide a VSB transmitter of about 300 W output power, which may be reduced to about 25 W for multi-station working (assuming pulse regeneration is employed). Phase

and amplitude linearity requirements are not stringent and are no more difficult than those met in existing television broadcast transmitters.

Pulse code modulation is a fairly old idea, but until recently not many multichannel equipments were made for commercial use, so that system evaluation has not been extensively pursued.

5.1.3 SSB Systems

The design of an SSB transmitter at these frequencies, with an output power in the range 5–20 kW (mean) with a total harmonic distortion figure more than 57 dB below PEP over the 5 Mc/s baseband used for trunk working, is a very difficult proposition indeed. The problem is easier for multi-station working; output powers in the range 1–5 kW mean are sufficient, and the basebandwidth occupies only 0.5 Mc/s.

5.2 SATELLITE EQUIPMENT

The attainment of that excellence of mechanical and electrical design, which is necessary for an active communication satellite to operate reliably and successfully in its predetermined orbit, is one of the major achievements of world-wide engineering effort over the past few years. This discussion, however, is limited to consideration of the basic electrical system design of the communication equipment within the satellite.

As in line-of-sight systems, there are two possible types of satellite repeater—demodulating and non-demodulating.

The non-demodulating repeater is the simpler, since it performs only two basic functions; amplification, and frequency-shifting before retransmission. Either wideband RF amplification may be used throughout, or the incoming signal may first be changed to an intermediate frequency before being changed again to a different radio frequency. Figs. 4(a) and (b) show both methods of designing a non-demodulating repeater. There is no fundamental difference in the satellite equipment for either of the three modulation methods considered, although, of course, the detailed characteristics differ with each. Further, the basic design is the same for trunk or multi-station working.

The demodulating repeater is more complex since a larger number of operations have to be performed. The basic design depends on the type

of modulation employed, and may differ, dependent on whether trunk or multi-station rôles are envisaged. It is based on the principle of the back-to-back receiver and transmitter shown in Fig.5.

For trunk working, there is no operational preference for the use of either the demodulating or non-demodulating repeater. In this case, only one FM or PCM or SSB emission has to be amplified and re-transmitted, and there is no question of having to avoid inter-modulation between radio frequency carriers, each with its own group of sidebands.

For multi-station use with FM or PCM, the repeater has to perform the more difficult job of accepting several frequency-spaced carriers, and

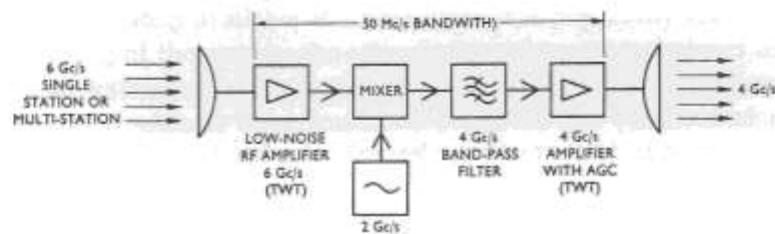


Fig.4a. Broadband non-demodulating satellite repeater. Amplification at radio frequency

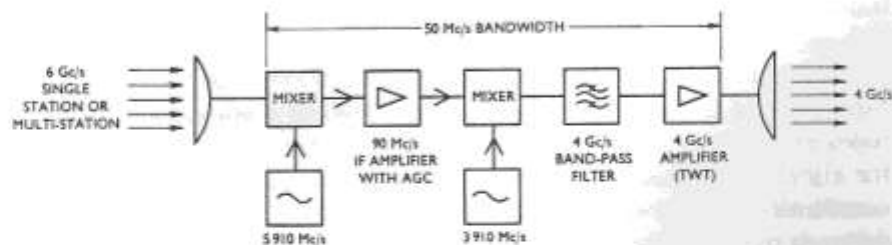


Fig.4b. IF type of non-demodulating satellite repeater

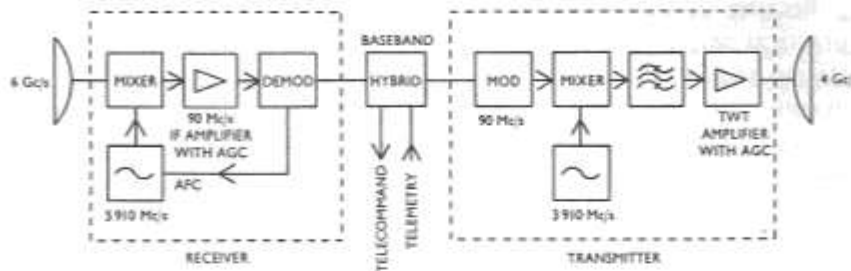


Fig. 5. Demodulating satellite repeater

their sidebands, and re-transmitting the information peculiar to each carrier.

The re-transmission of several FM signals from the satellite involves a theoretical minimum power requirement about 2 dB greater than for trunk working conditions, due to differences in loading factors. In addition, about 30% greater bandwidth is required to accommodate the necessary guardbands.

In SSB systems there is no corresponding distinction between trunk and multi-station use, since each 4 kc/s SSB emission is complete in itself whether it originates as one of 120 or one of 1200 channels. In the other modulation systems considered, groups of sidebands around a single carrier frequency carry the whole of the information from one locality. Multi-station SSB working therefore, whilst requiring an amplitude-linear receiver in the satellite repeater, gives a combined baseband output which requires no reprocessing or reassembly before being applied to the modulation input terminals of the satellite-to-ground transmitter. Either FM or SSB could be used for the satellite-to-ground link, although for the latter system, mean powers of up to 20 watts may be required, with good linearity.

If a distortionless wideband amplifier were available for use in the satellite (with frequency-shift to avoid feedback from output to input) either trunk or multi-station traffic could be relayed at will. The received signals on the ground would be subject to the double path Doppler shift, but compensation for this could be simply applied.

Because of the amplitude and phase non-linearity encountered in practical amplifiers (e.g. in TWT's and IF amplifiers), both FM multi-station and SSB (trunk and multi-station) systems are at a disadvantage in comparison with PCM, which can stand a high level (about -20 dB) of intermodulation between emissions carrying different coded information. Problems associated with the use of a common wideband amplifier are thus eased in the case of PCM.

For multi-station FM working, the type of repeater shown in Fig.6 offers a solution to the intermodulation problem. Here, separate IF

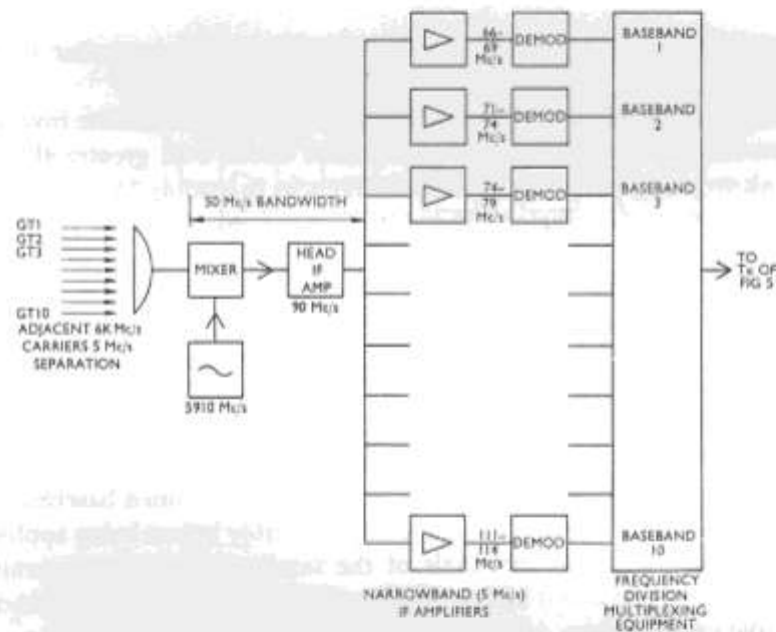


Fig.6. Demodulating satellite repeater for multi-station FM

Baseband outputs 1-10 resulting from transmissions from Ground Stations GT1-GT10 are either:
 (a) all in baseband 60-552 kc/s (120 channels); when FDM equipment is complex;
 (b) in 5 different 492 kc/s bands, when FDM equipment is simpler but ground station modulation efficiency is low, requiring higher power

amplifiers are used, followed by individual demodulation of each FM emission and re-grouping into a new FDM baseband signal before being applied to the modulation input terminals of an FM satellite-to-ground transmitter. This method seems very cumbersome and involves many processes, including the difficult one of assembling a 1200-channel baseband from ten separate 120-channel baseband groups. The number of components required would make the equipment bulky and, with present components, would result in an equipment reliability figure which is probably unacceptable in commercial systems.

6 CONCLUSIONS

The choice of the best modulation system to suit a given situation depends upon a number of factors. Consideration must be given to power, bandwidth, linearity, flexibility, possibility of interference and equipment complexity. In the face of this formidable list of factors, all of which may influence the final choice of the method of modulation, it is not easy to conclude that one particular system is better than another, unless the particular circumstances of its intended use are specified.

From an examination of Table I, which gives relative power and bandwidth requirements in various circumstances, it is evident that PCM is economical in the use of RF power when high channel S/N performances are prescribed. This is achieved at the expense of bandwidth.

SSB, on the other hand, demands high power and also, by current standards, very high amplitude linearity in all parts of the system. It also shows up worst when considering the possibilities of interference to and from the system. The main advantages of SSB are its flexibility regarding channel assignment for ground-to-satellite multi-station working, and its extreme bandwidth economy. In these respects it offers equipment simplicity, and the ability to form a combined baseband which is suitable for modulating the satellite-to-ground transmitter from the separate emissions of many ground stations. Pilot carriers, one for each ground station, would ease the problem of Doppler correction.

Complications on the satellite arise in the FM case when multi-station working is employed, since a multi-carrier problem exists which calls for either separate demodulation of each carrier and re-grouping into a

Table III
MODULATION SYSTEMS: PERFORMANCE SUMMARY

Factor Considered	Modulation System		
	SSB	FM	PCM
POWER REQUIREMENT	High. Difficult at present with required linearity	Medium. Achievable now	Medium. Achievable now
BANDWIDTH REQUIREMENT	Minimum	About 10 times minimum	As FM
LINEARITY REQUIREMENT	High. Difficult at present at required power levels	Difficult for common amplifier on satellite in multi-carrier case	Not too difficult on satellite or ground. Achievable now
FLEXIBILITY	Excellent. Separate assignment of each channel is possible	Restricted flexibility. Station maximum capacity must be pre-determined in frequency plan	As FM
INTERFERENCE	Given no added protection against incoming interference. High spectral density is liable to interfere with other systems	Increased protection against incoming interference. Can cause interference in lightly loaded cases	Good protection. Interference to other systems comparable with fully loaded FM case
EQUIPMENT COMPLEXITY	Uncomplicated, but high specification (e.g., power, linearity)	Trunk: Simple development of existing equipment. Multi-Station: Complex if demodulating repeater is necessary	Trunk: Simple repeater equipment. Multi-Station: Easier than in the FM case

new FDM baseband, or for the use of wideband RF and IF amplifiers of high linearity. The PCM case is similar, but the linearity requirement is lower and the design problem of both the wideband non-demodulating satellite repeater and of the ground equipment is eased.

Relative merits and difficulties associated with SSB, FM and PCM are briefly summarized in Table III.

If PCM is used on the upward path it is desirable, for reasons of equipment simplicity, to use PCM on the downward path also. On the other hand, upward transmission of SSB could be combined with downward transmission of either SSB or FM, FM at present being the more practical. FM in both directions is the third possibility.

PCM in both directions is attractive and offers good promise, but requires equipment development and further assessment. Since a number of PCM/VSB emissions may be assembled on a frequency-division basis, and may be passed through a common amplifier of limited linearity, multi-station operation using existing types of non-demodulating repeater equipment in the satellite should be possible.

SSB in the upward direction coupled with SSB or FM in the downward direction has much in its favour and will undoubtedly be used in some systems.

FM in both directions was in experimental use in the Telstar satellite, and initial tests have shown a performance capability equivalent to 600 telephone channels. Duplex FM working has also been achieved. Extension of this to the multi-station case is a step which would be greatly accelerated by the successful development of wideband non-demodulating repeaters of adequate linearity which can handle a large number of FM carriers simultaneously.

The multi-station concept of satellite communications opens up the possibility of providing cheaper low-capacity ground installations. These will be suitable for those regions where connection with the world telephone network is highly desirable, but the traffic requirements are limited. A 24 or 60 channel terminal would use an economical 30 ft aerial and a parametric amplifier (instead of the more costly and elaborate maser) thus presenting a more attractive proposition to the smaller administration.

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